Bonneville Power Administration
Fish and Wildlife Program FY99 Proposal

Section 1. General administrative information

Use Unsteady Flow To Aid Mainstem Passage Of Junenile Salmonids

Bonneville project number, if an ongoing project 9047

Business name of agency, institution or organization requesting funding
Oak Ridge National Laboratory

Business acronym (if appropriate) ORNL

Proposal contact person or principal investigator:

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Subcontractors.

Organization	Mailing Address	City, ST Zip	Contact Name

NPPC Program Measure Number(s) which this project addresses.
Measure 5.0E: Mainstem Passage Hypotheses; Measure 5.0F: Research and Monitoring; Measure 5.3 Snake River Reservoir Drawdown Strategy, Measure 5.3B.5: “Using best available scientific information regarding flow and velocity contributions , Measure 5.3B7.

NMFS Biological Opinion Number(s) which this project addresses.
B. O. Number 4, B. O. Number 10, B. O. Number 13g: The NMFS, in consultation with BPA, COE, BOR, and state agencies and tribes, shall design a study to evaluate the effectiveness of 'pulsing' flows for improving in-river survival of smolts."

Other planning document references.

Subbasin.

Short description.
Test the hypothesis that river flow hydraulics can aid fish migrations. Develop operation strategies for reservoir-river to provide unsteady and turbulent flows that are more favorable for successful migration of juvenile salmonids in Snake River.

Section 2. Key words

Mark	Programmatic Categories	Mark	Activities	Mark	Project Types
X	Anadromous fish		Construction		Watershed
	Resident fish		O & M		Biodiversity/genetics
	Wildlife		Production		Population dynamics
	Oceans/estuaries		Research		Ecosystems
	Climate		Monitoring/eval.	X	Flow/survival
	Other	X	Resource mgmt		Fish disease
			Planning/admin.		Supplementation
			Enforcement		Wildlife habitat enhancement/restoration
			Acquisitions		

Other keywords.
hydrodynamics, unsteady turbulent flow, modeling, reservoir operation, hydraulics, mainstem passage, salmonids

Section 3. Relationships to other Bonneville projects

Project #	Project title/description	Nature of relationship

Section 4. Objectives, tasks and schedules

Objectives and tasks

Obj 1,2,3	Objective	Task a,b,c	Task
1	Develop hydrodynamic model for Snake River-reservoirs system	a	Colecting data, evaluating and selecting models
		b	Detailed modeling of a typical river segment (Level 1)
		c	Modeling of river-reservoir system (Level 2)
2	Evaluate juvenile salmonids downstream migration in unsteady turbulent flow conditions	a	Testing hypothesis that river flow hydraulics can aid fish migrations
3	Estimate the channel lengths in the upstream portions of four sequential Snake River reservoirs	a	Simulating fish migration in river-reservoir system
4	Develop management strategies for reservoir-river system	a	Evaluate alternative flow and elevation measures for aiding downstream migrations of juvenile salmonids
5	Report results	a	Preparing final report and journal paper

Objective schedules and costs

Objective #	Start Date mm/yyyy	End Date mm/yyyy	Cost %
1	1/1999	6/1999	28.00%
2	4/1999	12/1999	20.00%
3	11/1999	5/2000	22.00%
4	3/2000	11/2000	23.00%
5	10/2000	12/2000	7.00%
			TOTAL 100.00%

Schedule constraints.

Completion date.
2000

Section 5. Budget

FY99 budget by line item

Item	Note	FY99
Personnel		$113,000
Fringe benefits		$41,750
Supplies, materials, non-expendable property		$ 350
Operations & maintenance		
Capital acquisitions or improvements (e.g. land, buildings, major equip.)		
PIT tags	# of tags:	
Travel		$3,600
Indirect costs		$35,000
Subcontracts		
Other	computing resources	$6,000
TOTAL		$199,700

Outyear costs

Outyear costs	FY2000	FY01	FY02	FY03
Total budget	$190,000			
O&M as % of total				

Section 6. Abstract

The ISG's review of science behind the Fish and Wildlife Program has uncovered strong evidence that juvenile salmonids use unsteady and turbulent flow characteristics (e.g., stage waves, turbulent bursts, vortices) as aids in maximizing downstream migration rate and distance per unit of energy expended by a fish. Assuming this to be true (although the weight of biological evidence would be aided by verification studies), reservoir management for optimal unsteady, turbulent flow hydraulics typical of rivers may be more biologically appropriate for aiding migration success than management for flow volume or velocity alone (the main factors considered today).

The proposed research is (1) to develop a computer model to test the hypothesis that river flow hydraulics can aid fish migrations; and (2) to develop management strategies for reservoir-river system to provide unsteady and turbulent flow conditions that are more favorable for successful migration.

The impact of fish utilization of flow hydraulics is twofold: (1) bioenergetics that salmonids can minimize the energy need for downstream migration; and (2) travel time

that determines the length of exposure to various stressors. Without thorough knowledge of the role of flow hydraulics in mainstem passage, the studies on other stress factors such as gas bubble trauma and thermal impact may be misleading. Seeking favorable flow hydraulics through reservoir management may be a more efficient and economical measure to achieve. It may be much less expensive to achieve unsteady and turbulent flow conditions that are favorable to fish migration than drawdown or other measures of water volume control to increase flow velocity and reduce travel time.

With two years of research effort, this study would quantify the length of reservoirs in the lower Snake River that would have unsteady and turbulent flows, which are favorable to fish migration behavior, under a range of river flow rates, reservoir elevations, and dam operations. Ultimate outcome of the project will be measured by the usefulness of the results for managing the hydrosystem for multiple purposes, including salmonid populations, as reflected in hydrosystem management plans of Bonneville, the Corps, agencies and tribes.

Section 7. Project description

a. Technical and/or scientific background.

Previous studies for relationships among flow, velocity, and survival for salmonids are based on over-simplified empirical relationship between flow (volume of water per time unity) and velocity (Cada et al. 1994). The increased velocity is assumed to be the biologically relevant feature of river flow increase for downstream migrating juvenile salmonids. Increased flushing of fish by higher water velocities is believed to be a major factor determining long-term fish survival. Fluid dynamics of water flowing in rivers has not been brought to answer the questions of salmon migrations. The methods of computer simulations continue to be developed. However the basic governing equations (i.e., continuity and momentum equations) for unsteady flow (varying with time) have been long established (Chow 1964, Cunge et al. 1980, and Chaudry 1993).

The normal pattern for a stream, viewed at the scale of a 50 mm to 150 mm fish, is to have velocities that change in often complex ways, whether viewed while moving along a longitudinal stretch or from one stationary point over time. These velocity changes can be in other directions as well as longitudinal (turbulence) and can be longitudinal pulses (traveling surges and flood waves). Increases in flow generally cause an increase in the water surface elevation. This increase in elevation travels away from the point of initiation as a wave, just as a stone tossed in the water creates a ring of waves (COE 1984, and Stoker 1957). These waves move faster than the water particles that make them up. Waves in moving streams can be propagated both upstream and downstream, but the upstream wave can be obliterated by the opposing streamflow. Thus, waves in streams caused by changes in flow (elevation) generally move downstream at a rate that is faster than the actual watermass by a factor of 1.3 (a general factor given first by Corbett 1943) to 4 (experimental data from the Snake River below Hells Canyon Dam in Koski 1974).

Turbulence is another feature of natural river hydraulics that might be used by migrating juvenile salmonids, and which is disrupted by impoundment. Turbulent burst is the high-speed, turbulent ejection of fluid and suspended solids away from the sediment bed, often after encountering a streambed obstruction (Leeder 1983). At distances 4-5 times the water depth, there are accelerated flow events acting toward the bed and concurrent rapid fluid movements away from the bed. The rising burst of flow propagates downstream in the water column and is seen at the water's surface as a "boil." A view of the surface of a swiftly moving river such as the unimpounded Columbia at Hanford, Washington, is of a patchwork of these boils. Water velocities in the leading edge of boils exceeds that of the general surrounding water. Unsteady bedload transport is driven by "bursting-type" cycles in the sea (Thorne et al. 1989) and Carling (1992) has suggested that riverine sediment transport is also related to the inherent turbulent structure of rivers. These velocity bursts are a function of flow rate and water depth; reduction of flow velocity and increase in depth (as in impoundments) would terminate such turbulence structures. As with solitary waves, it seems reasonable that salmonids emigrating in rivers would have evolved to make use of the zones of accelerated velocity in these turbulent bursts to assist them in downstream movement.

Vortices are another feature of turbulent flow, occurring in the horizontal plane rather than the vertical (as in bursts). Rows of vortices are shed behind solid bodies and trail behind in a wake. If the body is in midstream, there is a wake of roughly parallel vortices, forming first on one side and then the other. Each vortex rotates in the opposite direction of the preceding and succeeding ones. If the body is a projection from shore, the vortices trail in single file in what is often referred to as a shoreline "rip." In either case, water velocities on the outside of the wake of vortices is more rapid than the general (average) water flow. Solitary waves exist in streams, based on the accumulated knowledge of the field of open channel flow hydraulics and empirical evidence from field studies of the Snake River (Koski 1974); turbulent bursts also occur in streams (Carling 1992).

The ISG's review of science behind the Fish and Wildlife Program indicates that juvenile salmonids use unsteady and turbulent flow characteristics (e.g., stage waves, turbulent bursts, vortices) as aids in maximizing downstream migration rate and distance per unit of energy expended by a fish.

Experiments with drifting fish at thermal discharges at Hanford in the 1960s showed smolts traveling in the leading edges of boils (Becker and Coutant 1970; Becker et al. 1971). Ultrasonic-tagged adult chinook salmon and steelhead swam in the centers of shoreline rips (Coutant 1970), possibly using the upstream assist of vortices and suggesting that downstream-migrating juveniles would also be adapted to using such assists in the downstream direction. Averaged over long distances (several kilometers) in the Snake River with considerable length of riverine reach, steelhead smolts traveled faster than the average water particle (Berggren and Filardo 1993), suggesting either some assist or intense swimming that is difficult to justify based on the likely energy expenditure (Brett 1967; Trump and Leggett 1980). Averaged over similarly long distances, steelhead in the mostly impounded mid-Columbia River moved slower than water particles (Berggren and Filardo 1993), suggesting that they did not have the benefit of an assist (consistent with there being less wave effect in deep water of a reservoir).

Yearling chinook salmon in the Snake River, although not migrating as fast over the long distance as steelhead, nonetheless showed an average migration rate close to that of water particles (Berggren and Filardo 1993), which implies movement faster than water particles during the limited hours of the diel cycle when they actually move. Spring chinook smolts followed in their downstream migration with radiotelemetry moved fastest (and faster than water particles) in the riffle areas of the Willamette River (Schreck et al. 1995). Rainbow trout observed in streams by Northcote (1962) in infrared light headed downstream, near the water surface, and swam at a speed greater than the surrounding water (he did not look for waves or turbulence). All downstream migrants probably do not use these mechanisms, because underyearling chinook salmon migrate slowly and tend to orient head upstream until high velocities make them drift (Nelson et al. 1994). The historical Snake River between Lewiston and Pasco looks like the sort of channel that could have propagated solitary waves quite effectively, whereas the present string of reservoirs would be unlikely to do so (this clearly needs more analysis).

In principle, lowering reservoir elevations and increasing river flows would each result in a lengthening of the reach of upper reservoir where river-like flow hydraulics occur. Non-steady-state operation of dams undoubtedly induces unsteady flows. There is a need, therefore, to quantitatively estimate the lengths of river-reservoir reaches that would have unsteady and turbulent flows (for assisting the biological behaviors associated with successful fish migrations) at alternative flow rates, reservoir elevations, and dam operations.

b. Proposal objectives.

(1) Develop hydrodynamic model(s) for Snake River-reservoirs system.
(2) Run the model(s) to test the hypothesis that river flow hydraulics can aid fish migrations.
(3) Develop estimates of the channel lengths in the upstream portions of four sequential Snake River reservoirs that would be characterized by unsteady and turbulent flow hydraulics at a series of river flow rates, reservoir elevations, and non-steady-state operations of dam releases.
(4) Evaluate alternative flow and elevation measures for aiding downstream migrations of juvenile salmonids through the reservoirs using these channel lengths.
(5) Results will be published in final report and peer review journal paper.

c. Rationale and significance to Regional Programs.

With the wave dynamics going on in a stream, it would be surprising if a migratory fish species did not adapt to make use of the localized enhanced velocities and particle movements at wave fronts. Impoundments in a stream system could, in principle, affect the suggested wave phenomena and thus influence the migratory capabilities of salmon smolts. Some dams likely release water in pulses, generating a similar wave effect to that suspected in a natural system. On the other hand, the physical barrier of a dam would be an effective terminator of a downstream-propagating wave coming from upstream. Well upstream of the actual dam, a widening and deepening reservoir would, based on wave propagation theory, serve to diminish the wave height and thus the downstream transport of particles in the wave front. Fish riding waves might be left stranded in a small zone of the upper reservoir where they could be vulnerable to predation or other damaging effects.

The rationale behind the proposal is to apply the matured technology of open channel computational fluid dynamics to understand/explain the observed phenomena that fish can migrate downstream faster than the actual watermass.

The proposed project is relevant to the following Fish and Wildlife Program Measures and Biological Opinion Numbers:

- Measure 5.0E: Mainstem Passage Hypotheses: “One relationship is the effect of flow, water velocity and fish travel time on fish survival.”
- Measure 5.0F: Research and Monitoring (Mainstem Passage): The Council joins with the National Marine Fisheries Service and other regional interests in insisting that relationships between spring and summer flow, velocity and fish survival immediately receive the highest priority in the region’s research efforts.
- Measure 5.3 Snake River Reservoir Drawdown Strategy: “Snake River flow augmentation and transport measures, described in Sections 5.2 and 5.8, will be pursued pending implementation of the Snake River reservoir drawdowns.”
- Measure 5.3B.5: “Using best available scientific information regarding flow and velocity contributions to life-cycle survival and experience with juvenile passage in connection with Lower Granite drawdown …”
- Measure 5.3B7: “…fund ongoing evaluation of reservoir and life-cycle survival consequences of drawdowns.”
- B. O. Number 4: The COE shall operate lower Snake River pools within one foot of minimum operating pool."
- B. O. Number 10: The COE shall complete necessary feasibility, design, and engineering work to allow drawdown of Snake River reservoirs to begin by 2000."
- B. O. Number 13g: The NMFS, in consultation with BPA, COE, BOR, and state agencies and tribes, shall design a study to evaluate the effectiveness of 'pulsing' flows for improving in-river survival of smolts."

d. Project history

N/A

e. Methods.

(1) Develop hydrodynamic model(s) for Snake River-reservoirs system.

Data Collection

Data availability is one of the key factors in selecting appropriate hydrodynamic model for the proposed study. The stream flow hydrodynamic models are generally categorized into one, two, and three spatial dimensions, based on the degree of simplification in space domain. In general, three-dimensional models require much more detailed computational grids, bathymetry data for rivers (lakes and reservoirs), boundary and initial conditions and much greater computer (CPU) time. Data required for estimate channel hydraulics includes channel bathymetry, substrates, bottom roughness, reservoir operation and flow information (spatial and temporal velocity and water depth distribution for initial and boundary conditions). It is expected that much of the channel morphological information for Lower Granite, Little Goose, Lower Monumental, and Ice Harbor reservoirs can be obtained from the U. S. Army Corps of Engineers, whose cooperation and assistance with the project will be essential.

Development of Hydrodynamic Models

Hydraulic models would be set up for Lower Granite, Little Goose, Lower Monumental, and Ice Harbor reservoirs. Because numerous open channel hydrodynamic models have been developed in last three decades, appropriate models will be selected from the existing models and modified if necessary for this study. The model selection criteria considered include a) model capability and limitations, b) assumptions and approximations, and c) data requirement. Although the principles of continuity and momentum governing equations remain the same, most of the unsteady flow models require various approximations and simplifications to solve the equations numerically. The numerical methods vary depending on time and spatial integration. The time integration is usually carried out by finite-difference method (time-stepping) for which the scheme can be explicit or implicit, single or multiple step with low or high order. The implicit method requires to solve system equations with large storage requirement. The explicit scheme is more strength forward but subject to the limitation of Courant stability condition, which usually limits the time step increment to be small resulting high overall computer CPU time requirement. Spatial integration is more complex process which involves spatial discretization into a numerical network in one- two- or three-dimension. In general, there are two classes of numerical schemes: finite-difference (FD) solutions and finite-element (FE) solutions. The finite-element methods are usually much more computationally complex, and many of the exiting models rely on excessive numerical damping for the their application (Gary 1982).

(2) Test the hypothesis that river flow hydraulics can aid fish migrations.

The hydrodynamic model requires spatial capability in order to simulate unsteady (e.g., stage waves) and turbulent flow in the river (e.g., turbulent bursts, vortices) and to identify the most efficient fish migratory paths. Therefore, multi-dimensional (two- and/or three-dimensional) models should to be evaluated and tested. However, it is not feasible to run three-dimensional unsteady model for the region of Lower Granite, Little

Goose, Lower Monumental, and Ice Harbor reservoirs due to the exhaustive data and computational efforts required in three-dimensional modeling. Two levels of modeling efforts are designed for this study: a) a two- or three-dimensional model for a short river segment and b) one- or two-dimensional model for the whole system. Detailed modeling at Level 1 is to study (1) stage wave induced by reservoir operation, (2) spatial turbulent characteristics in the river (vertical and lateral distributions), (3) distribution of flow stream lines (possible fish downstream migratory paths) with respect to speed and travel time, and (4) relationships between wave propagation and stream line (vertical and lateral) distribution. Results of Level 1 modeling will provide guidance to compensate the spatial simplicity in Level 2 for the river-reservoir system.

Juvenile salmonids migration mechanisms will be studied and coupled with the hydraulic model. Migration mechanisms consider various fish's orientation and behavior during downstream migration such as passive drift, rest/feed, and swimming. Fish travel time at various flow conditions simulated from the coupling of unsteady flow model with fish migration will be compared and analyzed with fish data collected in the previous studies. Mean fluid velocity averaged over the channel cross-section and mean flow travel time will be used as the baseline conditions to compare with Juvenile salmonids downstream migration rate.

3) Develop estimates of the channel lengths in the upstream portions of four sequential Snake River reservoirs that would be characterized by unsteady and turbulent flow hydraulics at a series of river flow rates, reservoir elevations, and non-steady-state operations of dam releases.

Level 2 unsteady state hydraulic model coupled with fish downstream migration will be run under existing reservoir management conditions. Distances (river kilometers) with unsteady or turbulent flow would be compared for different flow and elevation conditions, and mathematical descriptions of the relationships would be provided for each reservoir. River flows and reservoir elevations to be evaluated would be indexed to the performance capability and recent history of the river system, as well as to management options (such as flow augmentation and reservoir drawdowns) already under consideration.

(4) Evaluate alternative flow and elevation measures for aiding downstream migrations of juvenile salmonids through the reservoirs using these channel lengths.

In a second year of effort, modeling efforts would be extended to additional considerations of alternative dam operations (drawndown, steady, or pulsed) and structural modifications of the reservoirs that might increase unsteady, turbulent flows for the benefit of fish. Additional physical data on the river-reservoir system that are not currently available might be needed to obtain in second year, so that hydraulic estimates can be refined. Analyses will also be extended to additional management options, integration of results with biological data.

(5) Preparation of final project summary report and manuscript for open literature publication.

f. **Facilities and equipment**.

Oak Ridge National Laboratory provides excellent computing facilities ranging from workstations to high performance parallel super computer. No special purchase for computer is expected.

g. **References**.

References

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Section 8. Relationships to other projects

Significance of this proposed project is also highlighted in temporal, scientific, and economic aspects:

Temporal Aspect

The hypothesis of river flow hydraulics and mainstem passage of salmonids needs to be tested before other individual stressors to be studied. Salmonids may not subject to all the stressors; they have to endure the flow hydraulics influenced by reservoir operation.

Because the river flow hydraulics will likely affect fish migrations, this need should be fulfilled before conducting reservoir drawdown studies.

Scientific Significance

The impact of fish utilization of flow hydraulics is twofold: (1) bioenergetics that salmonids can minimize the energy need for downstream migration; and (2) travel time that determines the length of exposure to various stressors.

The need is one of the keys to understand the interaction of multiple stressors from a reservoir-river system viewpoint instead of an isolated river segment. The flow hydraulics may be one of the critical factors contributing to the cumulative stress, fitness, and survival of out-migrating salmonids. Without thorough knowledge of the role of flow hydraulics in mainstem passage, the studies on other stress factors such as gas bubble trauma and thermal impact may be misleading.

Economic Significance

Seeking favorable flow hydraulics through reservoir management may be a more efficient and economical measure to achieve. It may be much less expensive to achieve unsteady and turbulent flow conditions that are favorable to fish migration than drawdown or other measures of water volume control to increase flow velocity and reduce travel time.

Section 9. Key personnel

PI: YIXING (STEVE) BAO

Research Staff member, Environmental Sciences Division, Oak Ridge National Laboratory, Building 1505, Mail Stop 6036, P.O. Box 2008, Oak Ridge, TN 37831-6036

Ph.D., Civil Engineering, University of Texas at Austin, 1992
M.S., Civil Engineering, University of Wyoming, 1987

B.S., Agricultural Engineering, Zhejiang Agricultural University, PRC, 1982

Employment History:

1995 to Present, Research staff, Environmental Sciences Division, Oak Ridge National Laboratory.

1994 to 1995, Post-doctoral research associate fellow, Oak Ridge Associated Universities, Oak Ridge, Tennessee.

1989 to 1994, Project Engineer/Hydrologist, Environmental Systems Section, Texas Water Development Board, Austin, Texas.

1982 to 1985, University Instructor, Department of Agricultural Engineering, Zhejiang Agricultural University, PRC.

Qualifications:

Extensive experience in research on two-dimensional open channel hydraulic modeling, watershed modeling, water quality analyses, environmental impact assessment, aquatic habitat evaluation, surface water pathway modeling for low-level waste performance assessment, and contaminated sediment transport in river basin. I developed computer codes including: DIRIFR for direct habitat analyses and INDIFR for indirect habitat analyses to assess the environmental impacts associated with hydropower development; OPTCALI combining nonlinear optimization and an expert system to automate calibration of watershed and water quality modeling, and HWBFDA using flow duration analysis to assess headwater benefits. I also improved a two-dimensional finite element hydrodynamic model (RMA2) by adding adaptive time step control routines to improve model convergence and to reduce CPU time, and improved a sediment transport model (STUDH).

Publications

Waste Area Grouping 2 Phase I Remedial Investigation: Sediment and Cesium-137 Transport Modeling Report, ORNL/ER-367, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1996, with R. Clapp.

Surface Water Pathway Modeling for Low-level Waste Performance Assessment, report to Office of Nuclear Material Safety and Safeguards, Nuclear Regulatory Commission, 1996, with M. Sale.

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Environmental Impact Statement (EIS) for Nine Proposed Hydroelectric Projects in the Skagit River Basin, Washington, FERC/EIS-0083-D, Federal Energy Regulatory Commission, Washington, D.C., 1994, with C. Coutant.

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“New Methodology for Optimization of Freshwater Inflows to Estuaries,” *J. Water Resources Planning and Management*, 120(2), 199-217, 1994.

“Evaluation of Uncertainty in Flood Magnitude Estimator on Annual Expected Damage Costs of Hydraulic Structures,” *Water Resources Research*, 23 (11), 2023-2029, 1987.

Section 10. Information/technology transfer

One final report in ORNL /TM format, two conference preceding papers, and two peer reviewed journal papers are expected.

Computer programs developed from this project can also be distributed.

Programs and papers are to be listed in ORNL Web sites.